

Development and Testing a Method for Retrieving Atmospheric Aerosol Optical Thickness based on the Solar Intensity from the Sun-photometer Data

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Abstract

The context of atmospheric aerosols is an indispensable aspect in studying the Earth's radiation budget, climate change, and air quality. Therefore, the quality technique in retrieving aerosol parameters is important for a better understanding their characteristics. The precise calculating of the aerosol physical parameter in the planetary boundary layer will increase the accuracy of evaluation of their impact on environmental conditions. In several atmospheric corrections of optical remote sensing using satellite sensors, the AOT's values play an important role in arranging a Look Up Table (LUT) for scattering parameters. Therefore, this study aims to develop a method for processing and correcting the sun-photometer data to obtain the original AOT in the planetary boundary layer. In AOT calculation using the sun-photometer data, the solar radiation at the extraterritorial of the atmosphere is determined using the Langley plot. Then, using the target data at the same season as the data for the Langley plot, the temporal change of AOT is estimated by employing the Lambert-Beer Law with some corrections. The major correction for the AOT's values computation in the measurement target is the contribution of molecule from the local station and Ozone (O₃) from the GOME-2 satellite data. The result has been compared with an independent measurement using a sky-radiometer at the same time as the sun-photometer monitoring. From the overall procedure, the AOT's values have uncertainties at approximately 2-5% compared to the sky-radiometer. Therefore, the procedure will be useful for studying aerosol optical properties in the lower troposphere.

Keywords

Aerosol, Atmosphere, GOME, Sun-photometer, Sky-radiometer

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1. INTRODUCTION

The study of global climate change and the earth's radiation budget discusses the significant effects of gaseous pollutants and aerosol particles in the lower troposphere (Change, 2007; Steinfeld, 1998). The atmosphere layer near the ground is where most of the atmospheric aerosol sources are loading. The aerosols are the tiny particles loading in the planetary boundary layer. The precise measurement of their parameters, especially in the lower layer of the atmosphere, is indispensable for improving the understanding of their characteristics. In addition to various sampling measurements, monitoring and analyzing the aerosol parameters has widely been used in optical remote sensing technology (Kuze, 2012b).

Estimating aerosol radiative forcing in the lower troposphere is one of the general analyses of the aerosol impact

on the global climate. The following are several parameters of aerosols relating to the radiative effects, i.e., aerosol extinction coefficient (AEC), Asymmetry Parameter, Single Scattering Albedo (SSA), and Aerosol Optical Thickness (AOT) (Chung, 2012). An improvement of the monitoring method that enables the retrieval of their optical properties is needed to obtain a better understanding of the physical parameter of aerosols (Chung, 2012; Kuze, 2012a). Through the lidar equipment, the spatial profile of AEC can be obtained by employing the Fernald method. The AEC is an attenuation of light in the ambient atmosphere. The AOT is an integration of AEC in the vertical distribution. In the radiative transfer context, the asymmetry parameter determines the particle's scatter radiation (preferentially to the front or back) and describes the angular distribution of the scattered radiation. Furthermore, Single Scattering Albedo (SSA) is the ratio of scattering efficiency to

total extinction efficiency. The parameter is indispensable for estimating aerosols' Direct Radiative Forcing (DRF) (Aminuddin, 2019; Aminuddin et al., 2018a; Fernald, 1984; Kinjo et al., 2001).

Extinction coefficient and optical thickness are the fundamental optical parameters for describing the influence of aerosol particles in the atmosphere layer. From a mathematics point of view, the aerosol optical thickness (AOT) usually operates as the integration of aerosol extinction coefficient (AEC) over the whole range of altitude, from the surface to the top of the atmosphere (Aminuddin et al., 2019; Aminuddin et al., 2018b; Fernald, 1984; Kinjo et al., 2001; Zieger et al., 2010). For the vertical direction in the ambient atmosphere, the Aerosol Extinction Coefficient (AEC) is represented as a function of the wavelength and altitude. The AEC represents the light attenuation due to the combined effects of scattering and absorption (Chen et al., 2014; Titos et al., 2014; Zieger et al., 2013). The time series values of AOT can be obtained through measurements using the sun-photometer and calibration using the Langley plot (Aminuddin et al., 2018a; Cerqueira et al., 2014; Chen et al., 2009; Chubarova et al., 2016; Qiu, 1998; Shaw, 1983).

The Aerosol Optical Thickness (AOT) measured using the sunphotometer provides parameters related to the attenuation of solar radiation in the opposite direction of several ground measurements. The light attenuation is monitored from the extraterritorial atmosphere to the planetary boundary level (Chung, 2012; Kuze, 2012b). Therefore, the AOT derived from the sun-photometer is an essential parameter for the atmospheric correction in satellite remote sensing and visibility degradation due to atmospheric pollution (Kuze, 2012a). Besides the different physical and chemical characteristics, the wavelength variation in AOT observation is also crucial for obtaining aerosol parameters in optical remote sensing using satellite sensors. The other essential application of the AOT, with its wavelength dependence, is valuable for monitoring the influence of clouds (Aminuddin et al., 2018c; Cerqueira et al., 2014; Chen et al., 2009; Chubarova et al., 2016).

An indispensable parameter for obtaining the AOT is the solar intensity at the top of the atmosphere. Due to the extraterrestrial solar intensity being challenging to monitor using independent measurement, their values are sometimes determined to be assumed based on aerosol type with the range between 0 to 1 in AU (Cerqueira et al., 2014; Qiu, 1998). The approximation procedure in the previous study employed the Langley plot and Lambert-Beer Law based on the sun-photometer data in the clear sky condition (Aminuddin et al., 2018c). Since the solar intensities' values at the top of the atmosphere depend on the seasonal change of the distance between the Sun and Earth, the air mass based on the sun-photometer data in the clear sky condition is employed as the approximation procedure. The choice of the clear sky condition is the state when the small aerosol loading in the ambient atmosphere. The air mass in this present study is estimated using the time series of the solar zenith angle. Besides, the general method to

derive original AOT from the sun-photometer data was usually only corrected using the sky-radiometer using loss correction (Aminuddin et al., 2019; Nelli et al., 2021; Evgenieva et al., 2022; Wu et al., 2022). The new method problem is challenging to implement in the location without the sky-radiometer instruments' support. Therefore, the purpose of this study is the development and test the method for obtaining logarithmic solar intensity from the extraterritorial atmosphere and the original AOT using the molecule from the local station and Ozone from the GOME-2 satellite. As a validation, the monitoring processes are implemented in the same area completed by the sky-radiometer as the certified instrument in obtaining the original AOT.

2. EXPERIMENTAL SECTION

2.1 Methodology

The procedures applied in this development and testing methods are several steps. The first is processing the solar intensity from the extraterrestrial atmosphere recorded by the sun-photometer in a clear sky. The clear sky condition is employed for calculating the logarithmic solar intensity at the top of the atmosphere using the Langley plot. Then, the sun-photometer's target data is processed to obtain the total Aerosol Optical Thickness (AOT) using Lambert-Beer Law. Next, the total AOT is corrected based on the molecule from the local station and the Ozone from the GOME-2 satellite to retrieve the original AOT. The final step is comparison the methods in retrieving the original AOT from the sun-photometer to the independent measurement using the sky-radiometer. The instrument for testing the method is in Chiba University, Japan (Figure 1).

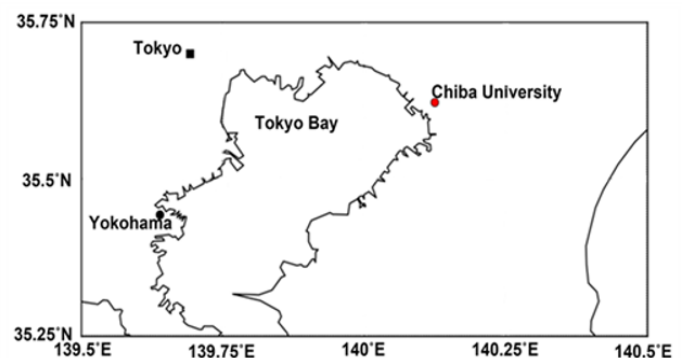


Figure 1. The Location of Instruments of the Sun-photometer and Sky-radiometer

2.2 Data

As a sample of this procedure, Figures 2 and 3 show the data for the Langley plot procedure recorded in the clear sky condition (12 February 2017) at the season close to the measurement target. The data in clear sky conditions estimates the logarithmic solar intensity. Figure 2 shows the data of the solar zenith angle

and azimuth angle, plotted manually based on data recorded by the sun-photometer instrument. Figure 3 is the sample data of the solar intensity obtained from the sun-photometer in the lower aerosol loading near the target measurement season.

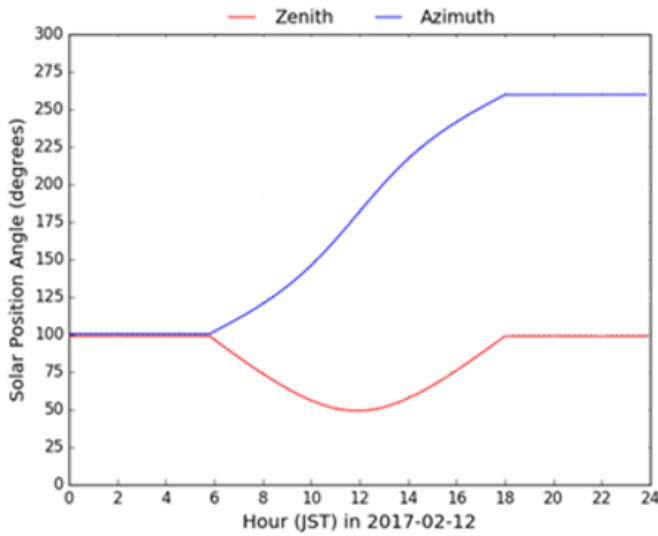


Figure 2. The Solar Zenith Angle and Solar Azimuth Angle on 12 February 2017

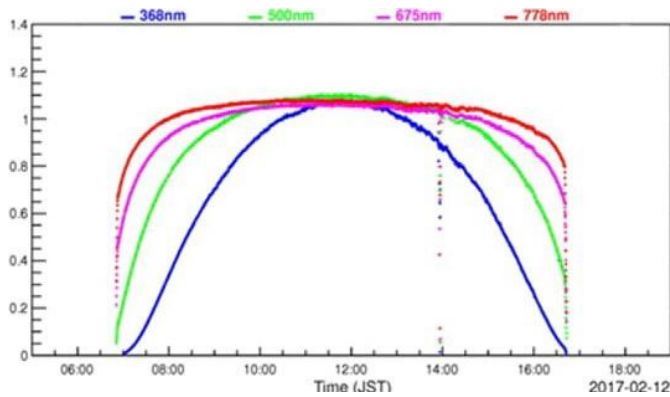


Figure 3. The Intensities of Solar Radiation with Four Wavelengths on 12 February 2017 Which is are Plotted Automatically by the Sun-photometer System

The measurement target is decided on 20 March 2017 because the atmosphere is in the middle, between turbid and clear, and cloudless. Figure 4 shows the solar intensity data in the four wavelengths with values lower than 1 AU. As the correction data, the Ozon map in Figure 5 and the air pressure series in Figure 6 are employed to calculate the contributions of gases and molecules. The temporal changes of air pressure on the day of measurement target are derived from the sun-photometer system, which is plotted manually.

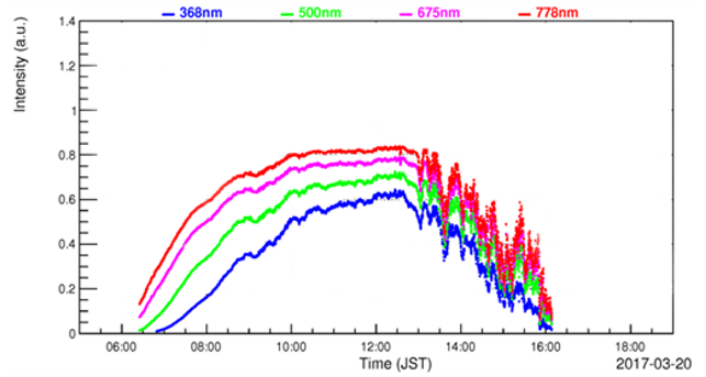


Figure 4. The Solar Intensity Data Was the Target of AOT Calculation on 20 March 2017

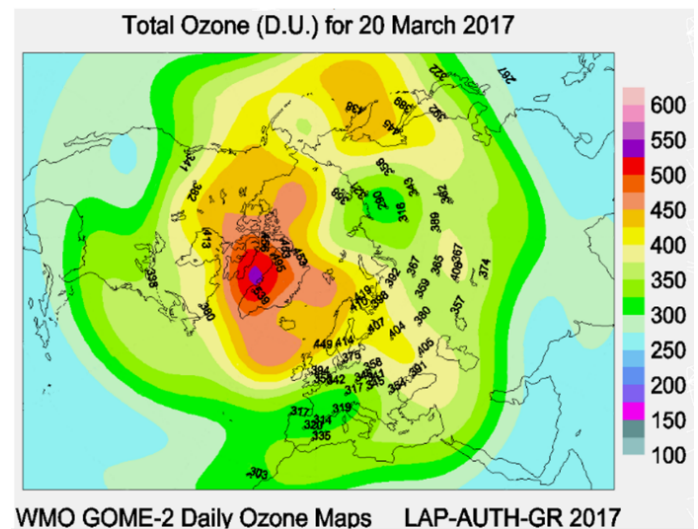


Figure 5. The Sample of Ozon Data Was Derived from the GOME-2 Satellite on 20 March 2017

2.3 Method

In this study, the sun-photometer is utilized to retrieve solar radiation's attenuation from the extra-terrestrial to the planetary boundary layer. The degradation of solar intensity from the extra-territorial atmosphere is caused by scattering from air molecules and aerosols. The attenuation is also due to the absorption of gases such as Ozone, Carbon dioxide, Oxygen, and water vapor (Kaufman, 1993; Manago et al., 2011). Figure 7 shows the scheme of the sun-photometer in measuring the solar intensity data.

AOT can be retrieved through the Langley plot and Lambert-Beer Law (Cerqueira et al., 2014; Chung, 2012; Qiu, 1998). The Langley plot is applied for calibrating the sun-photometer under a condition of minimal and stable aerosol accumulation. The basic form of the Langley extrapolation method can be written as

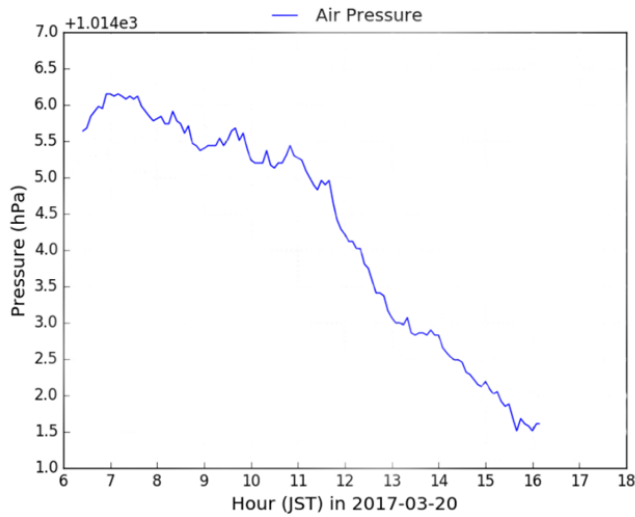


Figure 6. The Temporal Change of Air Pressure on 20 March 2017

$$\ln(I_\lambda) = -\frac{\tau\lambda}{\mu} + \ln(S_\lambda) \tag{1}$$

Here, I_λ and S_λ are estimated and measured of the solar intensity, respectively. Both are represented for every wavelength (λ) at the far-end boundary layer which is obtained from the sun-photometer measurement in the clear sky condition. The Langley plot is carried out using a definition that $x = 1/\mu = \sec\theta_s$, where θ_s is the solar zenith angle. In this plot, a linear Equation in the form $y=mx+c$, is formulated from $y=\ln(I_\lambda)$. Furthermore, the slope of the linear line and the y-intercept are represented as $m=-\tau\lambda$ (total optical thickness) and $c=\ln(S_\lambda)$, respectively. This approximation scheme shows in Figure 8, where both x and y data are plotted for obtaining $\tau\lambda$ and S_λ parameters. The air mass in this present study is estimated using the temporal change of the solar zenith angle in Figure 2 since the target is the solar intensity in the extra-terrestrial atmosphere (Cerqueira et al., 2014; Qiu, 1998). The sample data used for the study is shown in Figure 3.

Furthermore, as a report in references (Cerqueira et al., 2014; Qiu, 1998), by arranging Langley extrapolation methods and Lambert-Beer Law, an equation to derive the temporal change of AOT is represented in

$$\tau_A\lambda = \frac{\ln I(\lambda) - \ln I_C(\lambda)}{m\theta} - \tau_G(\lambda) - \tau_R(\lambda) \tag{2}$$

Indexes A, G, and R in Equation (1) represent the aerosol optical thickness (AOT), absorbing gases, and air molecules, respectively, as a function of wavelength (λ). Here, $I\theta$ is the solar intensity at the extra-territorial atmosphere derived from the Langley plot procedure, I is the solar intensity derived from the sun-photometer, and m is the air mass calculated from the solar

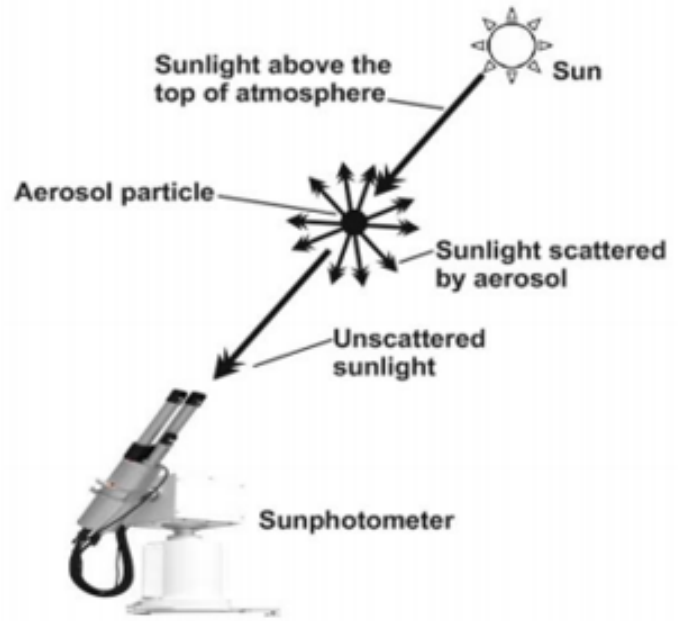


Figure 7. The Scheme for the Sun-photometer in Measuring the Solar Intensity

zenith angle (θ) on the target day (Figure 4). The correction factor in calculating AOT is ozone gases (O_3) derived from the GOME-2 satellite (Figure 5) and the molecules calculated from the local station using air pressure (Figure 6) (Aminuddin et al., 2018a; Aminuddin et al., 2018b; Aminuddin, 2019).

The time series values of the AOT of both absorbing gases and molecules in Equation (2) are computed from the following Equation.

$$\tau_G(\lambda) = 0 \times 10^{-3} \times f(\lambda) \tag{3}$$

$$\tau_R(\lambda) = \frac{P}{P_0} \times 0.00000864 \times \lambda^{-3.916+0.000074\lambda+\frac{50}{\lambda}} \tag{4}$$

In Equation (4), parameters $f(\lambda)$ and O represents the absorption coefficient and average of Ozone within the observation point, respectively. The Ozone concentration is written in Dobson Unit (DU), where 1 DU is equal to a 0.01 mm thick layer of pure Ozone at the standard temperature and pressure. Furthermore, P_0 and P are the air pressure constant (1013.26 hPa) and fluctuation, respectively. The ambient pressure can be seen in the local station simultaneously with the solar intensity measurement (Aminuddin et al., 2018a). Finally, the AOT values retrieved from data processing of the sun-photometer are compared with the sky-radiometer data as an independent measurement to estimate the accuracy of this procedure.

3. RESULTS AND DISCUSSION

Figure 9 shows the logarithmic solar intensity at the extraterrestrial atmosphere derived from the Langley plot procedure.

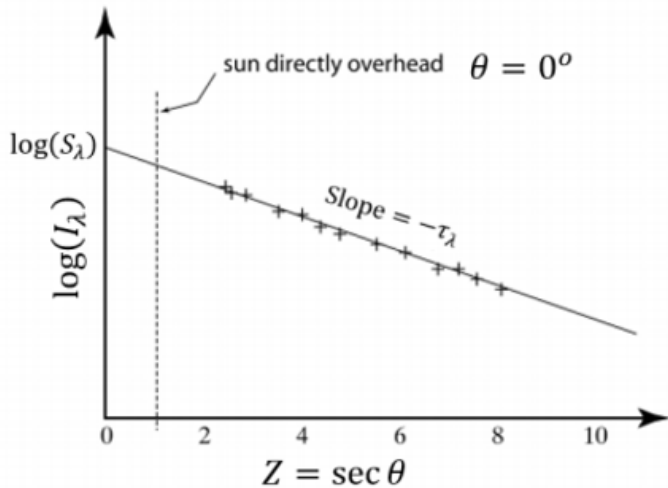


Figure 8. A Sketch of Langley Plot in Estimating the Logarithmic of the Extraterrestrial Solar Intensity in the Clear Sky Condition

The logarithmic solar intensity is represented in four wavelengths, i.e., ultraviolet ($\lambda=368$ nm), blue ($\lambda=500$ nm) and red ($\lambda=675$ nm), and near infrared ($\lambda=778$ nm). The values of the logarithmic solar intensity derived from the Langley extrapolation procedure are approximately at -14.797, -13.383, -13.119, and -14.151, respectively. The result corresponds to the pattern of the previous studies, where the shorter the wavelength, the higher the logarithmic solar intensity at the top of the atmosphere (Kaufman, 1998; Manago et al., 2011) (Aminuddin et al., 2018b; Aminuddin, 2019). Therefore, the results are capable of calculating the AOT using Lambert-Beer Law.

a wavelength of 368 nm (Cerqueira et al., 2014; Aminuddin, 2019; Wu et al., 2022). Although only one wavelength declines from the general result, the three wavelengths (500, 675, 778 nm) are similar trends. Therefore, a correction procedure is needed to compute the original AOT. The temporal change of the original AOT can be seen in Figure 11. In this study, we employ the correction based on the Ozone gas using the GOME-2 satellite and molecule using air pressure data which can be seen in Figures 5 and 6, respectively. The total AOT from 6 to 13 o'clock on the target day looks consistent, while from 13 to 16 o'clock fluctuates. The ambient conditions cause it, so the data recorded by the sun-photometer also fluctuate (it can be seen in Figure 4).

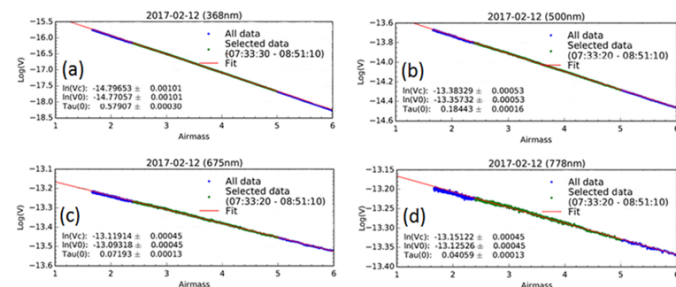


Figure 9. The Langley Plot of the Sun-photometer Data Was Observed on 12 February 2017. The Extrapolation Resulted the Logarithmic of the Solar Intensity at from the Extraterrestrial Atmosphere for every Wavelength (a) $\ln I_0$ (369)=-14.797, (b) $\ln I_0$ (500)=-13.383, (c) $\ln I_0$ (675)=-13.119, and (d) $\ln I_0$ (778)=-14.151.

Figure 10 shows the total AOT derived from the sun-photometer without corrections. Since the AOT is a dimensionless parameter with a maximum of 1, the results are inconsistent with the general values, especially for the blue band with

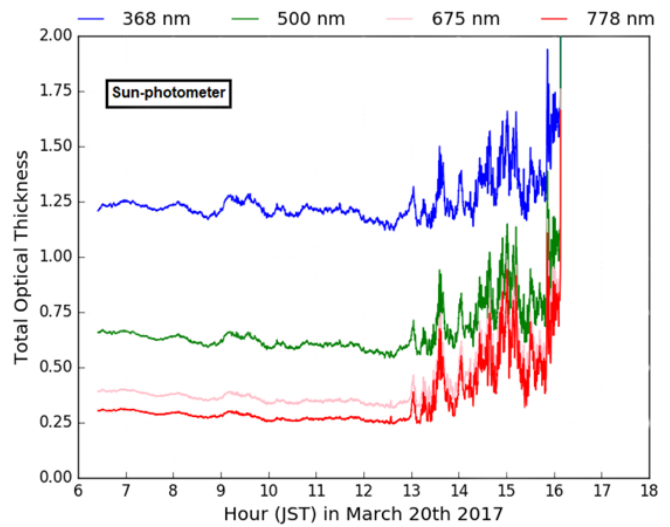


Figure 10. The Total of AOT Without Correction

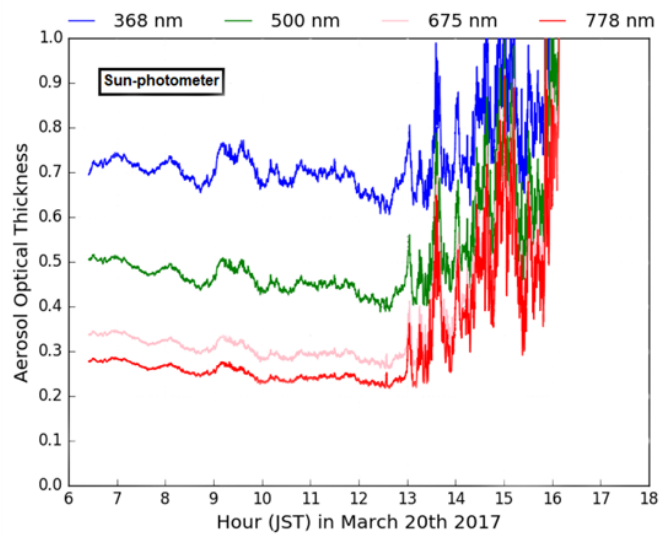


Figure 11. The Original AOT Was Corrected by Gases and Molecule

As a validation, the monitoring processes are implemented in the same area completed by the sky-radiometer as the certified instrument in obtaining the original AOT. Figure 12 shows the time series of the original AOT in seven wavelengths (340, 380, 400, 500, 675, 870, and 1020 nm). Although there are some different numbers of the wavelengths between the sun-photometer and sky-radiometer, the AOT values of both instruments are relatively in the same pattern. The values of the original AOT derived from the sky-radiometer at 13 to 16 o'clock are relatively stable. However, the sun-photometer data at a similar time fluctuate. Therefore, a comparison of the result in this study is only performed for the original AOT from 6 to 13 o'clock.

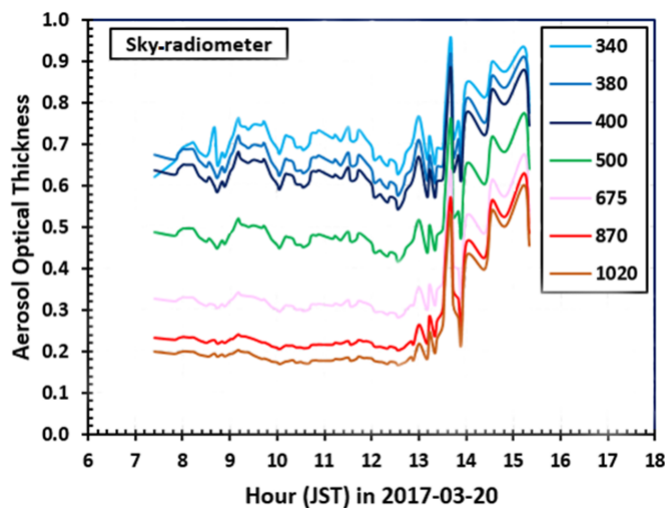


Figure 12. The AOT is Derived from the Sky-radiometer as the Certified Measurement

Figure 13 shows the temporal change of the original AOT for the wavelength at 500 nm, which has been compared with the observed value from the sky-radiometer and the ground sampling instruments. The wavelength of 500 nm is selected considering the ground sampling instruments (an integrating nephelometer and an aethalometer). The ground sampling instruments are also installed in the exact location as the sun-photometer and sky-radiometer in Chiba University-Japan. The original AOT using the sampling instrument is retrieved from the procedure in reference (Aminuddin et al., 2018b; Aminuddin, 2019). From the overall procedure, the AOT's values have uncertainties at approximately 2 to 5% after comparing to the sky-radiometer. Therefore, the procedure will help study aerosol optical properties. On the other hand, the AOT's values derived from the ground sampling instrument by applying the previous study (Aminuddin et al., 2018a; Aminuddin, 2019) show a deviation of around 10 to 15%. The method applied in this study has demonstrated the usefulness of the Langley plot and Lambert-Beer Law for studying aerosol characteristics in the planetary boundary layer, where the vast aerosol particles are loading. Uninterrupted estimation of AOT

will provide new insight into the source and sink investigation of aerosols and in the monitoring of the local environment.

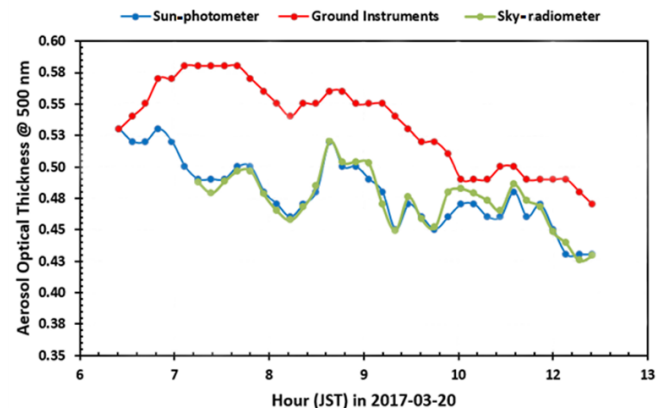


Figure 13. Comparison of the Original AOT Derived from the Sun-photometer and Sky-radiometer

The parameters utilized in this estimation are derived from applying several corrections. Comparing the method in processing the sun-photometer data (Xun et al., 2021; Bărbulescu, 2022), the Langley plot and Lambert-Beer Law are useful to support several methods in retrieving the solar intensity from the extraterrestrial atmosphere. In several atmospheric corrections of optical remote sensing using satellite sensors, the AOT's values play an essential role in arranging a Look Up Table (LUT) for scattering parameters (Aminuddin et al., 2018a; Jin et al., 2021; Kuze, 2012b).

4. CONCLUSION

A methodology for estimating the AOT from continuous data of the sun-photometer has been proposed and demonstrated based on the Langley extrapolation method and Lambert-Beer Law. The result has been compared with the sky-radiometer as an independent and certified instrument for retrieving the original AOT. The method is also compared to the ground-based sampling instruments (an integrating nephelometer and an aethalometer). It has been found that the AOT's values have uncertainties at approximately 2 to 5% after comparing to the sky-radiometer. Therefore, the procedure will help study aerosol optical properties. The current approach will be generally helpful in estimating the optical properties of ambient aerosols based on sun-photometer data.

5. ACKNOWLEDGEMENT

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